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MAINTAINABILITY AND RELIABILITY DESIGN OF A PRECISION HIGH CURRENT POWER SUPPLY

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Summary

This article describes the maintainability and reliability aspects of a precision high current dc power supply which uses high current thyristors, power transistors and integrated circuits. It was developed for continuous, 24 hours a day, 7 days a week operation in a large nuclear particle accelerator. Based on the life cycle cost concept, this is a low cost, industrial quality power control equipment.

The ease of maintenance is particularly important in this equipment because the downtime has to be kept to a minimum, once installed the servicing can be performed through the front door only and because of the large number of delicate components used. The ease of maintenance was designed-in by analyzing the probability of occurrence and the corrective steps required for various types of failure, and then building the equipment for minimum downtime and minimum corrective effort.

Introduction

Power Electronics has been described[1] as being interstitial to all major disciplines of Electrical Engineering, Power (Static and Rotating Equipment), Electronics (Devices and Circuits) and Control (Continuous and Sampled Data). This article describes the design of a specific piece of Power Electronics type of equipment, focusing specifically on the maintainability and reliability aspects. The specific piece of Power Electronics type of equipment described here, subsequently referred to as The Bias Supply, is one of many similar equipments used to control the flow of electric power as required for operation of a nuclear particle accelerator.

An accurate control of large blocks of electric power is fundamental to the design and operation of nuclear particle accelerators. The electric power in question is in the form of dc current through electromagnets shaped to produce the desired magnetic fields. The function of this equipment, the Ferrite Bias Supply or simply the Bias Supply, is to change the frequency of resonant cavity in a prescribed manner as required for acceleration of nuclear particles to high energies. There are 16 Bias Supplies in the Booster Accelerator and 15 in the Main Accelerator with additional units to be added. This description refers specifically to the improved version of the equipment, Mk II.

Definition of the Problem

The problem was to develop an equipment which meets its performance requirements under the following boundary conditions:

1. Fit into an allotted space.
2. Operate reliably.
3. Be easy to troubleshoot and repair.
4. Be relatively inexpensive to produce in small quantities (10 pieces).

The Bias Supply is required to produce an output current from 0 to 3000A dc into an inductive load of 130 microhenries in response to a 0 to 10V signal under the following conditions:

1. Current regulation and ripple less than 0.5A peak-to-peak in the range of 30 to 1000A and 2.5A peak-to-peak in the range of 1000 to 3000A.
2. Slewing rate of 200,000A/sec.
3. Small frequency response to 2 kHz (3 db down).
4. Be controllable from local and remote positions.

The functional diagram is shown in Figure 1. The 12 thyristors on the secondary side of the 200-kVA transformer perform most of the muscle work required in rectifying and rough control of current. To clean up the debris and other extra signal pollution generated by thyristors, 190 power transistors rated 150 watts each are used. These transistors operate in response to the input command and to the output current feedback signals. A fast responding solid state contactor (SSC) with its network of status sensors and comparators serves as a watchdog and makes sure that the equipment is not damaged in case of a component failure.

Maintainability Considerations

In the process of translating the functional diagram into reality, it was assumed that the equipment will fail, now and then, thus requiring troubleshooting, repair, removal and re-installation. Thus, during an estimated life of 10 years, the cumulative downtime due to equipment failure and necessary repair may be considerable. Since the downtime of this equipment may mean the downtime of other pieces of equipment in the operating chain, the total cost in effort and money during the 10-year period can be quite large. For these reasons, any steps taken during the design stage which minimize the cumulative downtime will pay dividends in the long run and also contribute toward personal satisfaction of the people involved.

Some of the specific design steps taken toward improved maintainability are:

1. Simplified installation and removal. This equipment has to be removed from its slow not only for its own servicing, but also for the servicing of some equipments adjacent to it. The disconnect (or connect) process consists of disconnecting the dc output bus bars, the 480V, 3-phase cables, 120V control power, the cooling water hoses and pulling the 4500-lb. unit out of its slot. As can be partially seen from the photograph in Figure 2, the removal task was made easier by:

a. Making the electrical connections accessible from the inside. The ac power cables present no particular problem, but a special quick-disconnect design had to be developed for the output bus bars, using a sandwich type bus bar construction and a one-bolt "O" clamp.

b. Large diameter, low friction casters.

c. Using quick-disconnect water hose fittings.

2. Status monitoring of the essential parameters at local and remote locations. Analog and digital monitors at the equipment are mounted on front panel above the front door as can be seen from Figure 3. The most essential parameter, the output current is monitored continuously by an indistrial type 250-degree ammeter. A similar, but zero center ammeter next to it and in conjunction with a 12 position selector switch, is used to selectively monitor any one of 12 parameters within the equipment. On the extreme right side of the panel are 14 pilot lights whose on or off condition signifies normal or abnormal condition of a particular variable. Finally, if the information conveyed by the status lights and the meters is not sifficient, then a single-ended oscilloscope can be connected to 1 or more of 14 BNC connectors for additional diagnosis.

3. Modular construction with quick connect/disconnect features.

4. Making the critical components accessible for servicing from inside of the equipment.

5. High voltage terminals are placed out of normal reach, labelled with warning signs and covered wherever possible.

6. Keying all connectors.

7. Provide fringe benefit features:
   a. AC service outlet.
   b. Drain valve on the cooling system.
   c. Door interlock bypass switch, etc.

8. Labelling and identification of various components.

Details of some of the features can be seen in Figure 4. In the upper left-hand corner are mounted 12 power transistor modules which are part of the active filter designed to remove the undesirable signals and to serve as a source of high frequency signals. Each module contains 15 power transistors connected in parallel as shown in Figure 5. Since it is essential that the transistors share the current equally, a solid wire circular loop has been included to accommodate the commercial clamp-on ammeters. By mounting the transistors on one water cooled bus bar and the corresponding emitter resistors and fuses on a similar bus bar, a sandwich-type construction results which is easy to assemble into a system, relatively simple to manufacture and has desirable electrical characteristics. The cooling manifolds located beneath the transistor modules provide approximately 1 gpm flow into each module making it possible to dissipate up to 1.5 kW per module. Quick disconnect, LRL type fittings, are used for connecting the individual modules to the manifolds.

In the lower right-hand corner is mounted a cooling water distribution panel. This panel contains a fine mesh strainer and a distribution manifold on the incoming line and a distribution manifold with 4 flow switches on the outlet side.

Directly above the plumbing panel is control electronics sub-assembly containing a printed circuit card bin with room for 8 pc cards and 2 connector panels, horizontal for the outside calbes and vertical for the inside connections. The top slot contains an extender card. The number of adjustable resistors is kept to a minimum.

The rectifier thyristors are accessible from the inside after removal of a shield panel. The gate and cathode leads are made readily available for testing and removal.

Reliability Considerations

The reliable operation as used in this description implies operation of the equipment per specification for extended periods of time, unattended and in case of a component failure, the other components are not damaged (fail-safe).

To achieve reliable operation, the design strategy followed was:

1. Use components designed for reliable operation in an industrial environment.

2. Operate the components within their safe operating area.

3. Provide fault isolation and protective circuitry to obtain fail-safe operation.

4. Design the equipment for the ease of maintenance.

Rectifier transformer and other electromagnetic components are at the foundation of the reliability pyramid structure. The rectifier transformer, rated at 200 kVA, was designed with the following features:

1. To have a minimum copper and core loss within the allotted size and cost. This is a significant consideration because it means lower cost during the life cycle of the equipment. The first saving occurs when paying for the smaller number of kW while operating, while the second saving occurs in the smaller bill for the air conditioning required for removal of the generated heat.

2. Use of Class H insulation and Class A temperature rise operation.
3. Use of water cooling.
4. Use of flow and over-temperature switches for protection.
5. Provide an electrostatic shield between primary and secondary windings.

A total of 180 power transistors in parallel are used in the active filter. A parallel operation implies that each transistor carries its fair share of the load, a condition difficult to achieve in practice, particularly under pulsed conditions. For reliable operation under these conditions, the following design steps were taken:

1. Power transistors with the highest safe operating area available were selected.
2. All transistors were selected for dc current gain, 100 ±20 at 2A.
3. Equalizing resistors, 0.2 ohms, 10W in each emitter was used.
4. Isolation fuse, indicating type, is used in each emitter.
5. Isolation diode in the base of each transistor is used.
6. The entire bank of 180 transistors is protected against over-voltage and against the second breakdown.
7. The entire bank is protected against over-current.

The above steps have prevented catastrophic failures, but we still find blown transistors and fuses under unusual operating conditions.

Another factor affecting the reliability is the vibration of components caused by the pulsed input program and harmonics of the power line frequency. To minimize the effect of vibration, flexible straps are used in critical areas, particularly the high current rectifier circuits.

Another major sub-system which contributes toward reliability is the Solid State Contactor (SSC). Functionally, this unit connects and disconnects the 300A, 480V, 3-phase, 60 Hz power to the Bias Supply in response to direct or protective commands. In response to the "ON" command, the "soft start" is obtained by phasing the thyristors to the fully ON condition. In response to "OFF" command, the gate driving signals to the thyristors are short circuited, causing the thyristors to block and thus to turn the power off within ½ power cycle. The thyristors themselves are protected against line transients by selinium type surge suppressors.

There are 3 types of "Off" commands:

1. Normal turn off in response to the manual actuation of a momentary push button in the local position or in response to a level transition of a logic signal at the remote position.

2. Malfunction turn off, actuated automatically in response to a critical component failure, insufficient water flow, over-current or over-temperature conditions. In case of each of these malfunctions, the contactor is automatically turned off and an alarm lamp at the local position and a logic 0 at the remote position are actuated. These alarm signals stay on until reset.

3. Panic shutdown actuated automatically by failure of control power, component failure within the contactor itself or by a logic 1 signal specifically provided for this purpose. A separate reset at the local and remote positions, is required after each actuation of the panic shutdown.

It is well known that the operating temperature has a direct bearing on reliability of the equipment. Most of the internally generated heat in this equipment is removed by 90° F. demineralized, low conductivity water. Sufficient flow in each critical component is maintained to assure that the component is operated within its safe operating area. Each major sub-assembly is protected by its own flow switch and a back-up bimetallic switch.

A fine mesh strainer is included to avoid the large particles from blocking the flow, while a turbine type flowmeter is included to measure the total flow and to establish the "cholestrol level" or blocking that may exist.

One of the sure ways of assuring a reliable system operation is to assure that the various sub-systems and components are operating properly. This was assured by designing the equipment for ease of maintenance and by providing the various diagnostic tools described previously. Thus the maintainability-reliability loop is closed: Easy to maintain equipment is more reliable and reliable operation is achieved by equipment that is easy to maintain.

Acknowledgements

Many people have contributed toward making the final product possible. I wish specifically to thank the management of Fermi National Accelerator Laboratory for providing an opportunity for me to do this work, Quentin Kerns for many ideas and inspiring conversations, and to the technicians, Jim Ziober, Joe Davis, John Reid and Dave Huffman for their many contributions.

References

1. W. E. Newell, Power Electronics - Emerging from Limbo, IEEE Trans. on Industry Applications, Vol. 1A-10, No. 1 Jan/Feb. 1974.

LIST OF FIGURES

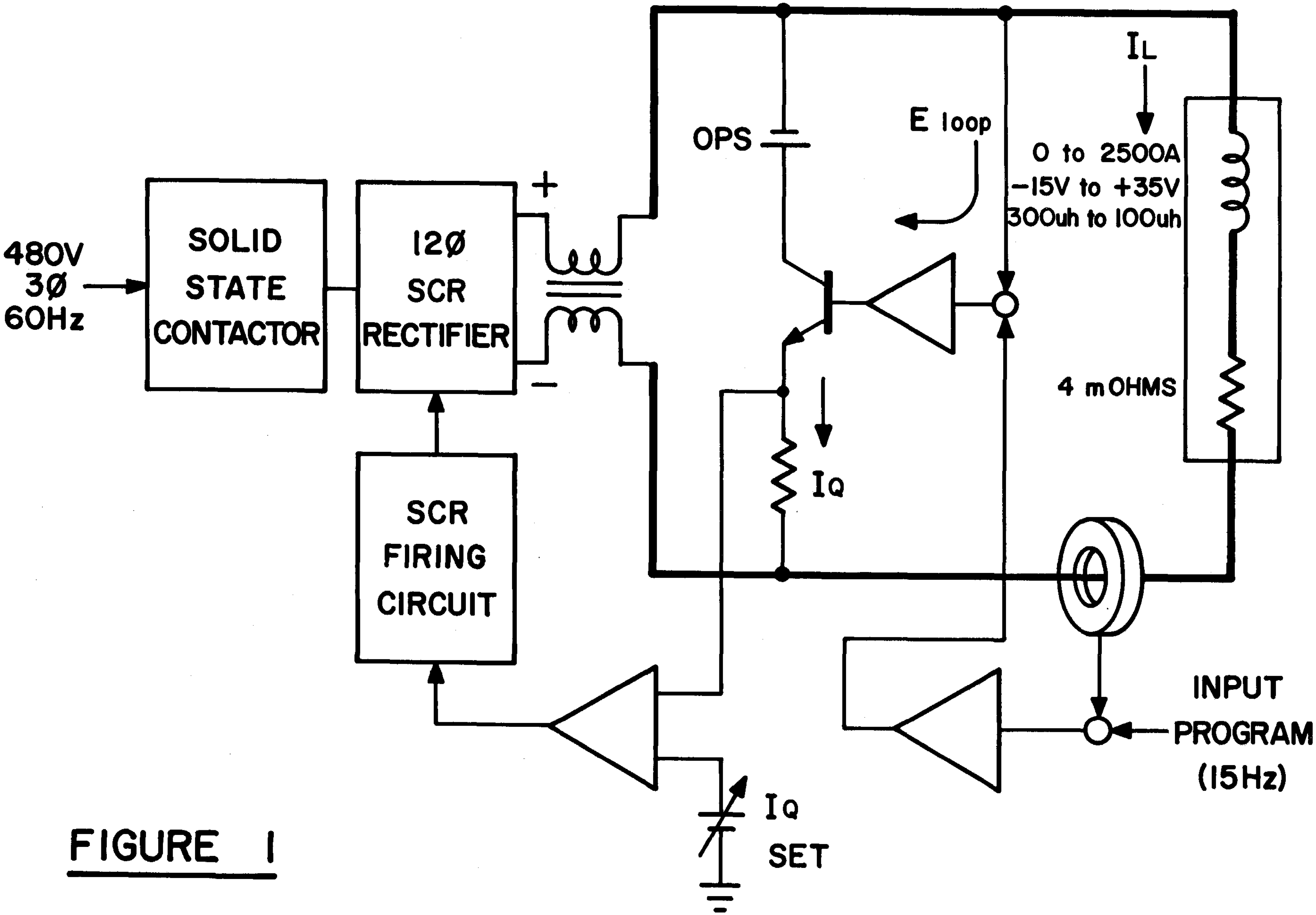

FIGURE 1

FUNCTIONAL DIAGRAM
OF THE FERRITE BIAS SUPPLY

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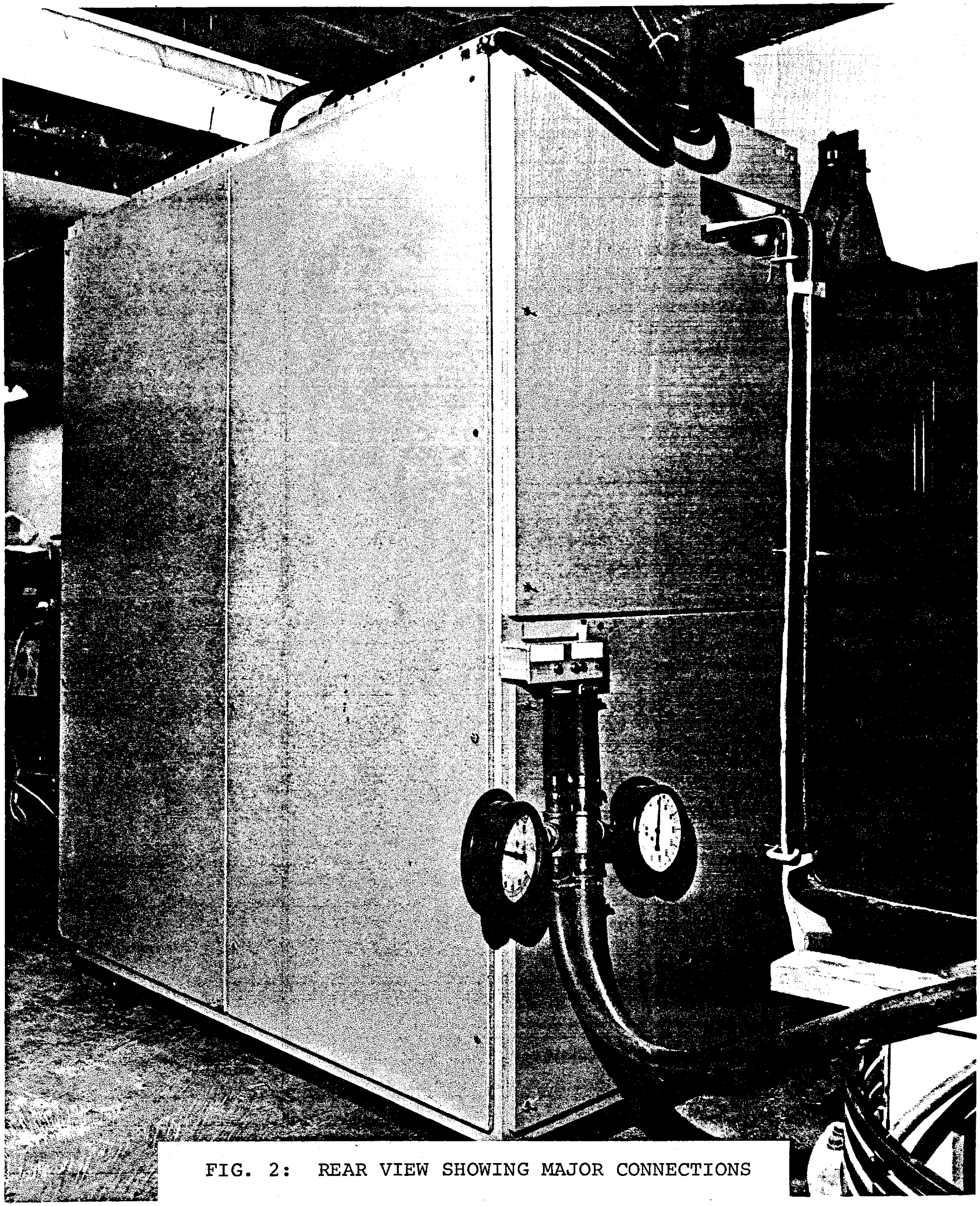

FIG. 2: REAR VIEW SHOWING MAJOR CONNECTIONS

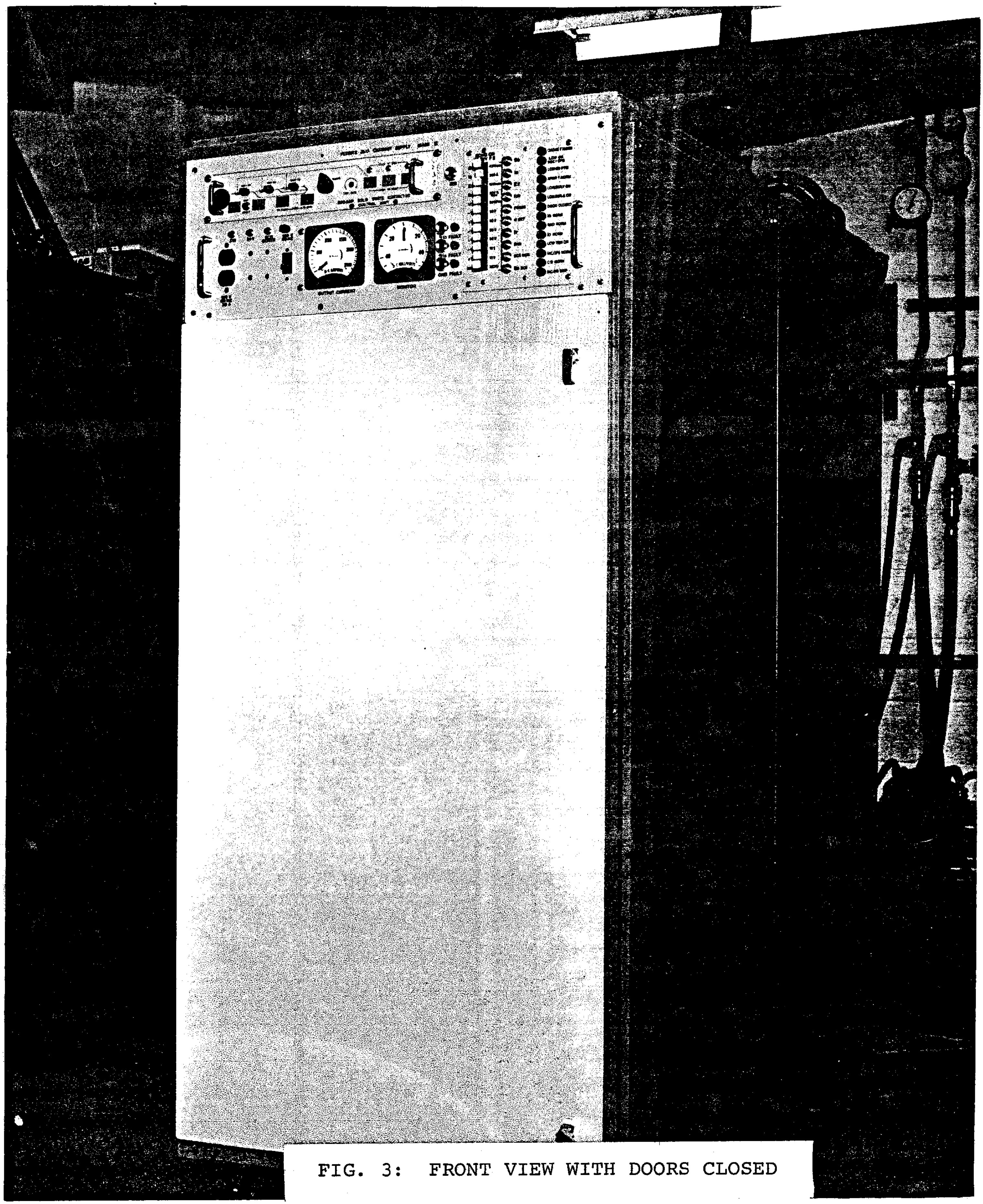

FIG. 3: FRONT VIEW WITH DOORS CLOSED

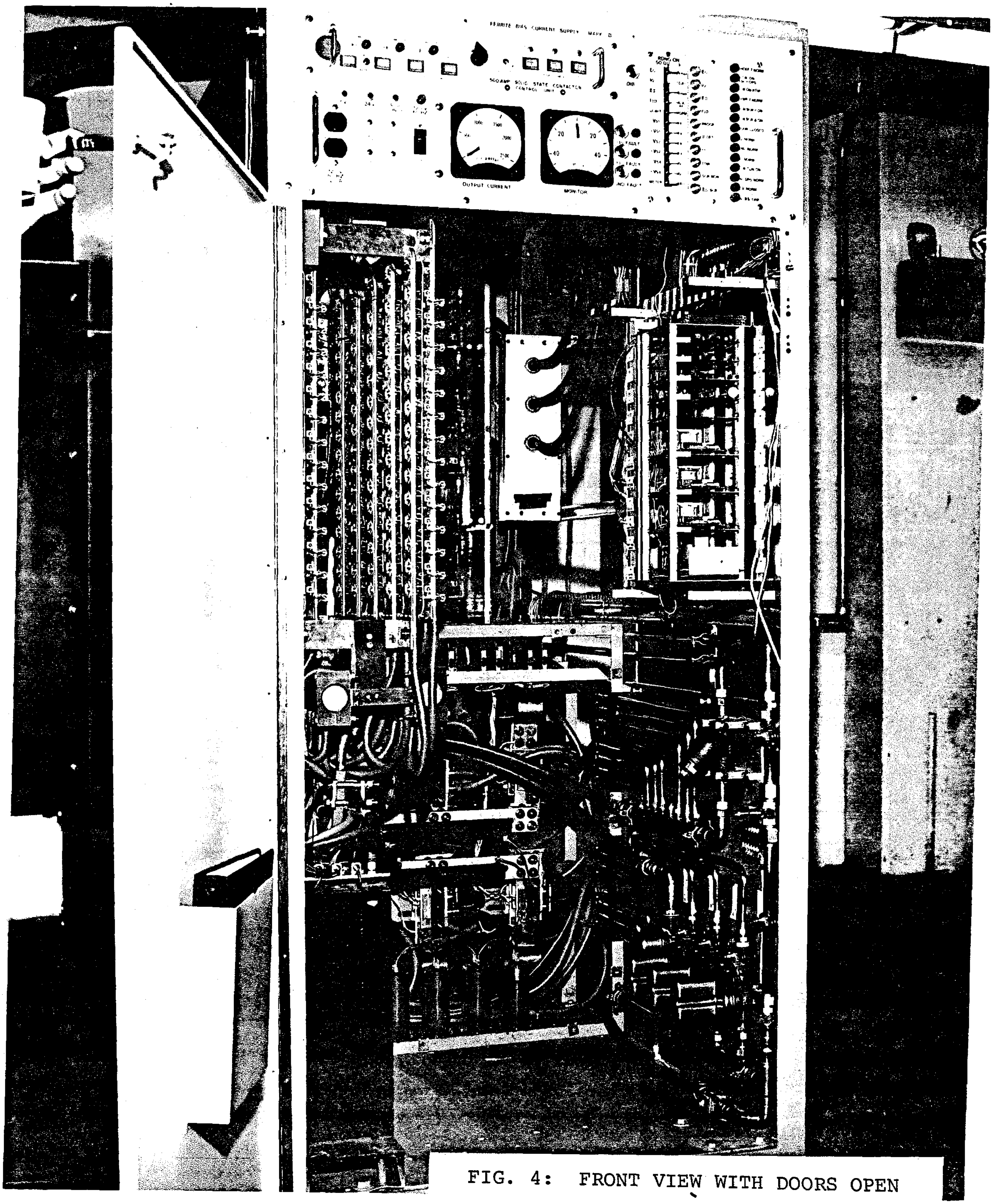

FIG. 4: FRONT VIEW WITH DOORS OPEN

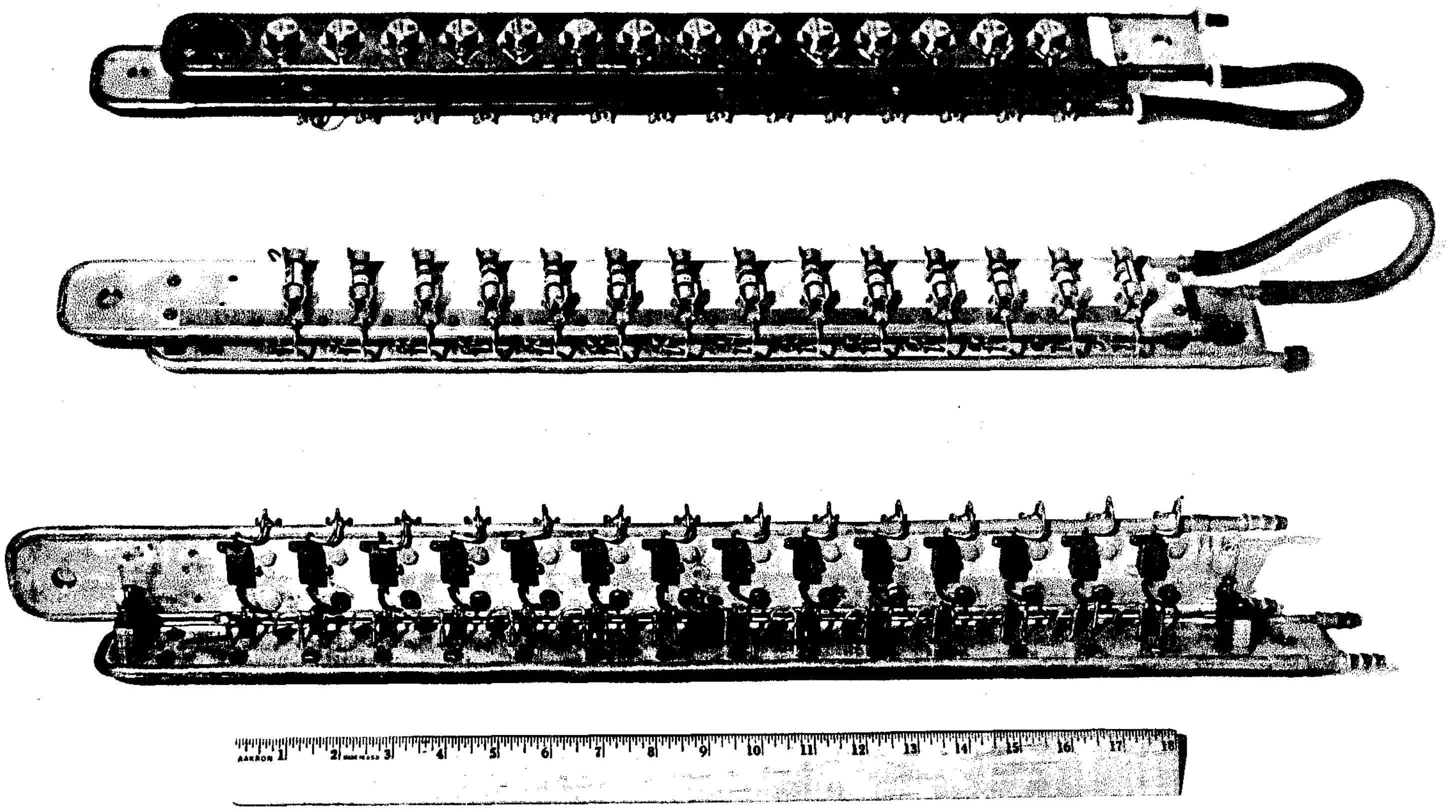

FIG. 5: POWER TRANSISTOR MODULE